APPENDIX K. LONG-TERM RADIOLOGICAL IMPACT ANALYSIS FOR THE NO-ACTION ALTERNATIVE

K.1 Introduction

This appendix provides detailed information related to the radiological impact analysis for No-Action Alternative Scenario 2, including descriptions of the conceptual models used for facility degradation, spent nuclear fuel and high-level radioactive waste material degradation, and data input parameters. In addition, this appendix discusses the computer programs and exposure calculations used. The methods described include summaries of models and programs used for radioactive material release, environmental transport, radiation dose, and radiological human health impact assessment. Although the appendix describes No-Action Scenario 1, it focuses primarily on the long-term (100 to 10,000 years) radiological impacts associated with Scenario 2.

NO-ACTION ALTERNATIVE SCENARIOS 1 AND 2

Under the Nuclear Waste Policy Act, the Federal Government has the responsibility to provide permanent disposal of spent nuclear fuel and high-level radioactive waste to protect the public's health and safety and the environment. DOE intends to comply with the terms of existing consent orders and compliance agreements on the management of spent nuclear fuel and high-level radioactive waste. However, the course that Congress, DOE, and the commercial nuclear utilities would take if there was no recommendation to use Yucca Mountain as a repository is highly uncertain.

In light of these uncertainties, it would be speculative to attempt to predict precise consequences. To illustrate one set of possibilities, however, DOE decided to focus the analysis of the No-Action Alternative on the potential impacts of two scenarios:

Scenario 1: Long-term storage of spent nuclear fuel and high-level radioactive waste at the current storage sites, with effective institutional control for at least 10,000 years.

Scenario 2: Long-term storage of spent nuclear fuel and high-level radioactive waste, with the assumption of no effective institutional control after approximately 100 years.

DOE recognizes that neither of these scenarios is likely to occur if there was a decision to not develop a repository at Yucca Mountain. However, the Department selected these two scenarios for analysis because they provide a baseline for comparison to the impacts from the Proposed Action and because they reflect a range of the potential impacts that could occur.

To permit a comparison of the impacts between the construction, operation and monitoring, and eventual closure of a proposed repository at Yucca Mountain and No-Action Scenario 2, the U.S. Department of Energy (DOE) took care to maintain consistency, where possible, with the modeling techniques used to conduct the *Viability Assessment of a Repository at Yucca Mountain* (DIRS 101779-DOE 1998, all) and in the *Total System Performance Assessment – Viability Assessment (TSPA-VA) Analyses Technical Basis Document* (DIRS 100355, 100356, 100357, 100358, 100359, 100362, 100364, 100365, 100366, 100369, 100371-CRWMS M&O 1998, all) for the proposed repository (see Appendix I, Section I.1, for details). In pursuit of this goal, DOE structured this analysis to facilitate an impact comparison with the repository impact analysis. Important consistencies include the following:

- Identical evaluation periods (100 years and 10,000 years)

- Identical spent nuclear fuel and high-level radioactive waste inventories at the reference repository:

  — Proposed Action: 63,000 metric tons of heavy metal (MTHM) of commercial spent nuclear fuel; 2,333 MTHM of DOE spent nuclear fuel; 8,315 canisters of high-level radioactive waste. This inventory includes an amount of surplus weapons-usable plutonium

  — Module 1: All Proposed Action materials, plus an additional 42,000 MTHM of commercial spent nuclear fuel; 167 MTHM of DOE spent nuclear fuel; and 13,965 canisters of high-level radioactive waste. This would result in a total of approximately 105,000 MTHM of commercial spent nuclear fuel; 2,500 MTHM of DOE spent nuclear fuel; and 22,280 canisters of high-level radioactive waste. This inventory also includes the surplus weapons-usable plutonium (see Appendix A, Figure A-2)

DEFINITION OF METRIC TONS OF HEAVY METAL

Quantities of spent nuclear fuel are traditionally expressed in terms of *metric tons of heavy metal* (typically uranium), without the inclusion of other materials such as cladding (the tubes containing the fuel) and structural materials. A metric ton is 1,000 kilograms (1.1 tons or 2,200 pounds). Uranium and other metals in spent nuclear fuel (such as thorium and plutonium) are called *heavy metals* because they are extremely dense; that is, they have high weights per unit volume. One metric ton of heavy metal disposed of as spent nuclear fuel would fill a space approximately the size of a typical household refrigerator.

- Consistent spent nuclear fuel and high-level radioactive waste corrosion and dissolution models
- Identical radiation dose and risk conversion factors
- Similar assumptions regarding the future habits and behaviors of population groups (that is, that they will not be much different from those of populations today)

Since issuing the Draft EIS, DOE has continued to evaluate design features and operating modes that would improve long-term repository performance and reduce uncertainty. The result of the design evolution process was the development of the flexible design (DIRS 153849-DOE 2001, all), which was evaluated in the Supplement to the Draft EIS. This design focuses on controlling the temperature of the rock between waste emplacement drifts. As a result of these design changes, this Final EIS evaluates a range of repository operating modes (higher- and lower-temperature). The lower-temperature operating mode has the flexibility to remain open and under active institutional control for up to 300 years after emplacement. Although Chapter 4 of this EIS includes an evaluation of impacts for this period, DOE did not evaluate the 300-year institutional control case for the No-Action Alternative. The primary reason for not updating this part of the analysis was because if the institutional control period for the analysis of the No-Action Alternative were extended to 300 years, the short-term environmental impacts would have increased by as much as 3 times. DOE did not want to appear to overstate the impacts from the No-Action Alternative.

Since the publication of the Draft EIS, DOE modified the spent nuclear fuel cladding corrosion rates and failure mechanisms used in the performance analysis in Chapter 5 of the Final EIS. DOE did not update these models for the No-Action Alternative Scenario 2 analysis because the outcome would have been an increase in the long-term radiation doses and potential health impacts, however, the increase would be within the uncertainties discussed in Section K.4. In addition, the radionuclide inventories for commercial spent nuclear fuel were updated for the Final EIS (see Appendix A, Tables A-8 and A-9) to reflect the higher initial enrichments and burnup projected for commercial nuclear facilities. Although these revised inventories were used to estimate potential short-term repository impacts in the Final EIS

(Chapter 4), DOE chose not to update the No-Action inventories because, again, the effect on the outcome would be about a 15-percent increase in health impacts in this chapter.

Affected populations for the No-Action Alternative were, in general, based on 1990 census estimates and not projected to 2035 as was done for the Proposed Action. However, if the population across the Nation had been projected to 2035, the collective impacts resulting from radiation exposure would have increased by less than a factor of 1.5, which is the average expected increase in national population from 1990 to 2035 (DIRS 152471-Bureau of the Census 2000, all).

For commercial facilities, the No-Action analysis estimated short- and long-term radiological impacts for Scenario 1 and short-term impacts for Scenario 2 during the first 100 years for facility workers and the public based on values provided by the U.S. Nuclear Regulatory Commission (DIRS 101898-NRC 1991, p. 21). For DOE facilities, radiological impacts for these periods under Scenarios 1 and 2 were estimated based on analysis by Orthen (DIRS 104596-Orthen 1999, all). To ensure consistency with the repository impact analysis, the long-term facility degradation and environmental releases of radioactive materials were estimated by adapting TSPA-VA process models developed to predict the behavior of spent nuclear fuel and high-level radioactive waste in the repository (DIRS 104597-Battelle 1998, pp. 2.4 to 2.9).

Because DOE did not want to influence the results to favor the repository, it used assumptions that generally resulted in lower predicted impacts (rather than applying the bounding assumptions used in many of the repository impact analyses) if TSPA-VA models were not available or not appropriate for this continuous storage analysis. For example, the No-Action Scenario 2 analysis took into account the protectiveness of the stainless-steel waste canister when estimating releases of radioactive material from the vitrified high-level radioactive waste; the TSPA-VA assumed no credit for material protection or radionuclide retardation by the intact canister. This approach dramatically reduced the release rate of high-level radioactive waste materials to the environment, thereby resulting in lower estimated total doses and dose rates to the exposed populations. Conversely, in many instances the TSPA-VA selected values for input parameters that defined ranges to ensure that there would be no underestimation of the associated impacts. Section K.4 discusses other consistencies and inconsistencies between the TSPA-VA and the No-Action analysis.

The long-term impact analysis used recent climate and meteorological data, assuming they would remain constant throughout the evaluation period (DIRS 101912-Poe and Wise 1998, all). DOE recognizes that there could be considerable changes in the climate over 10,000 years (precipitation patterns, ice ages, global warming, etc.) but, to simplify the analysis, did not attempt to quantify climate changes. Section K.4.1.2 discusses the difficulties of modeling these changes and the potential effect on outcomes resulting from uncertainties associated with predicting potential future climatic conditions.

Although the repository TSPA-VA used probabilistic process models to evaluate the transport of radioactive materials within Yucca Mountain and underlying groundwater aquifers, DOE used the deterministic computer program Multimedia Environmental Pollutant Assessment System (MEPAS; DIRS 101533-Buck et al. 1995, all) for the No-Action Scenario 2 analysis because of the need to model the transport of radioactive material. In addition, it discusses environmental pathways not present at the repository (for example, the movement of contaminants through surface water). The MEPAS program has been accepted and used by DOE and the Environmental Protection Agency for long-term performance assessments (DIRS 101917-Rollins 1998, pp. 1, 10, and 19).

K.2 Analytical Methods

This section describes the methodology used to evaluate the long-term degradation of the concrete facilities, steel storage containers, and spent nuclear fuel and high-level radioactive waste materials. In addition, it discusses the eventual release and transport of radioactive materials under Scenario 2. The

PROBABILISTIC AND DETERMINISTIC ANALYSES

A *probabilistic* analysis represents data input to a model as a range of values that represents the uncertainty associated with the actual or true value. The probabilistic model randomly samples these input parameter distributions many times to develop a possible range of results. The range of results provides a quantitative estimate of the uncertainty of the results.

A *deterministic* analysis uses a best estimate single value for each model input and produces a single result. The deterministic analysis will usually include a separate analysis that addresses the uncertainty associated with each input and provides an assessment of impact these uncertainties could have on the model results.

Analyses can use both approaches to provide similar information regarding the uncertainty of the results.

institutional control assumed under Scenario 1 would ensure ongoing maintenance, repair and replacement of storage facilities, and containment of spent nuclear fuel and high-level radioactive waste. For this reason, assuming the degradation of engineered barriers and the release and transport of radioactive materials is not appropriate for Scenario 1. The Scenario 2 analysis assumed that the degradation process would begin at the time when there was no effective institutional control (that is, after approximately 100 years) and the facilities would no longer be maintained. This section also describes the models and assumptions used to evaluate human exposures and potential health effects, and cost impacts.

K.2.1 GENERAL METHODOLOGY

For the No-Action analysis, the facilities, dry storage canisters, cladding, spent nuclear fuel, and high-level radioactive waste material, collectively known as the *engineered barrier system*, were modeled using an approach consistent (to the extent possible) with that developed for the Viability Assessment (DIRS 101779-DOE 1998, Volume 3). These process models were developed to evaluate, among other things, the performance of the repository engineered barrier system in the underground repository environment. In this analysis, the process models were adapted whenever feasible to evaluate surface environmental conditions at commercial and DOE sites. These models are described below.

Figure K-1 shows the modeling of the degradation of spent nuclear fuel and high-level radioactive waste and the release of radioactive materials over long periods. Five steps describe the process of spent nuclear fuel and high-level radioactive waste degradation; a sixth step, facility radioactive material release, describes the amount and rate of precipitation that would transport the radioactive material or *dissolution products* to the environment. This section describes each process and the results. Additional details are provided in reference documents (DIRS 101910-Poe 1998, all; DIRS 104597-Battelle 1998, all).

Environmental parameters important to the degradation processes include temperature, relative humidity, precipitation chemistry (pH and chemical composition), precipitation rates, number of rain-days, and freeze/thaw cycles. Other parameters considered in the degradation process describe the characteristics and behavior of the engineered barrier system, including barrier material composition and thickness. To simplify the analysis, the United States was divided into five regions (as shown in Figure K-2) for the purposes of estimating degradation rates and human health impacts (see Section K.2.1.6 for additional details).

Under the No-Action Alternative, commercial utilities would manage their spent nuclear fuel at 72 nuclear power generating facilities. DOE would manage its spent nuclear fuel and high-level radioactive waste at five DOE facilities [the Hanford Site (Region 5), the Idaho National Engineering and Environmental Laboratory (Region 5), Fort St. Vrain (Region 5), the West Valley Demonstration Project (Region 1), and the Savannah River Site (Region 2)]. The No-Action analysis evaluated DOE spent

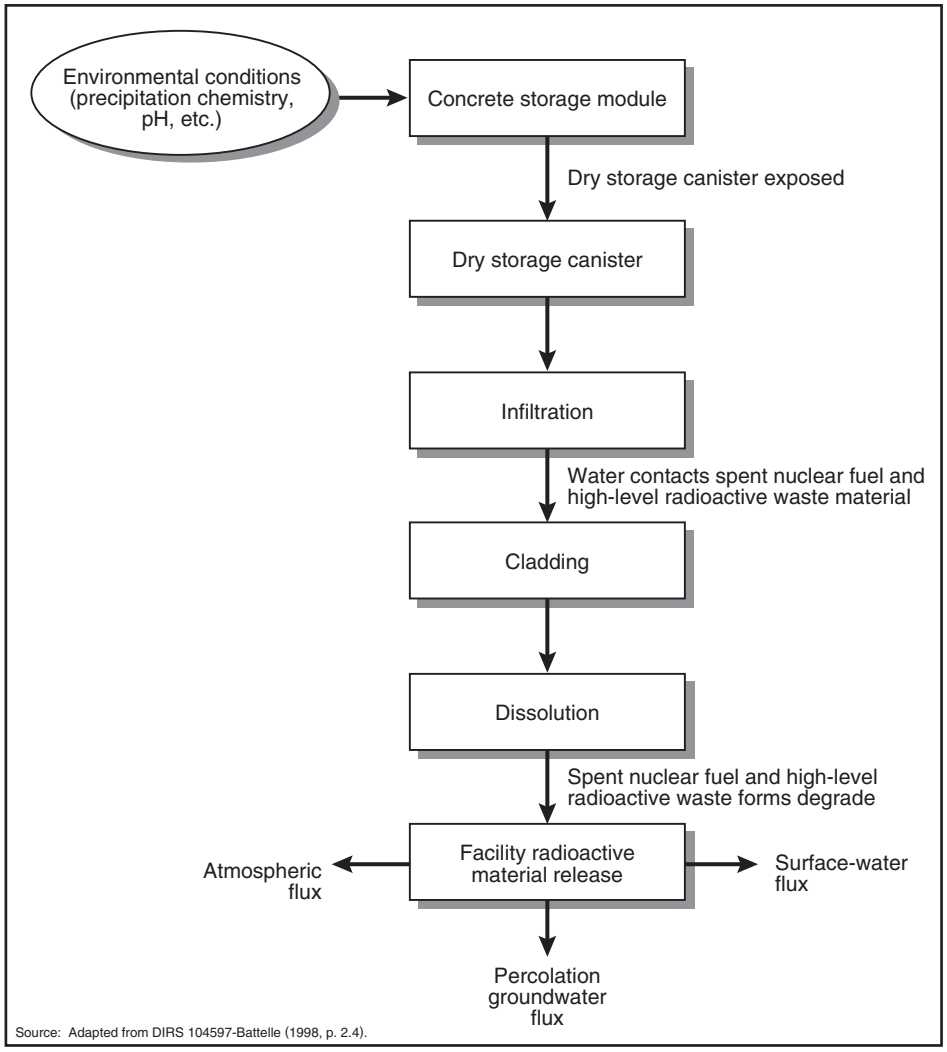

Figure K-1. Primary steps and processes involved in the degradation of the engineered barrier system.

nuclear fuel and high-level radioactive waste at the commercial and DOE sites or at locations where Records of Decision have placed or will place these materials (for example, West Valley Demonstration Project spent nuclear fuel was evaluated at the Idaho National Engineering and Environmental Laboratory (60 *FR* 28680, June 1, 1995). Therefore, the No-Action analysis evaluated DOE aluminum-clad spent nuclear fuel at the Savannah River Site and DOE non-aluminum-clad fuel at the Idaho National Engineering and Environmental Laboratory. DOE evaluated most of the Fort St. Vrain spent nuclear fuel at the Colorado site. In addition, the analysis evaluated high-level radioactive waste at the West Valley Demonstration Project, the Idaho National Engineering and Environmental Laboratory, the Hanford Site, and the Savannah River Site.

K.2.1.1 Concrete Storage Module Degradation

The first process model analyzed degradation mechanisms related to failure of the concrete storage module. *Failure* is defined as the time when precipitation would infiltrate the concrete and reach the spent nuclear fuel or high-level radioactive waste storage canister. The analysis (DIRS 101910-Poe 1998, Section 2.0) considered degradation due to exposure to the surrounding environment.

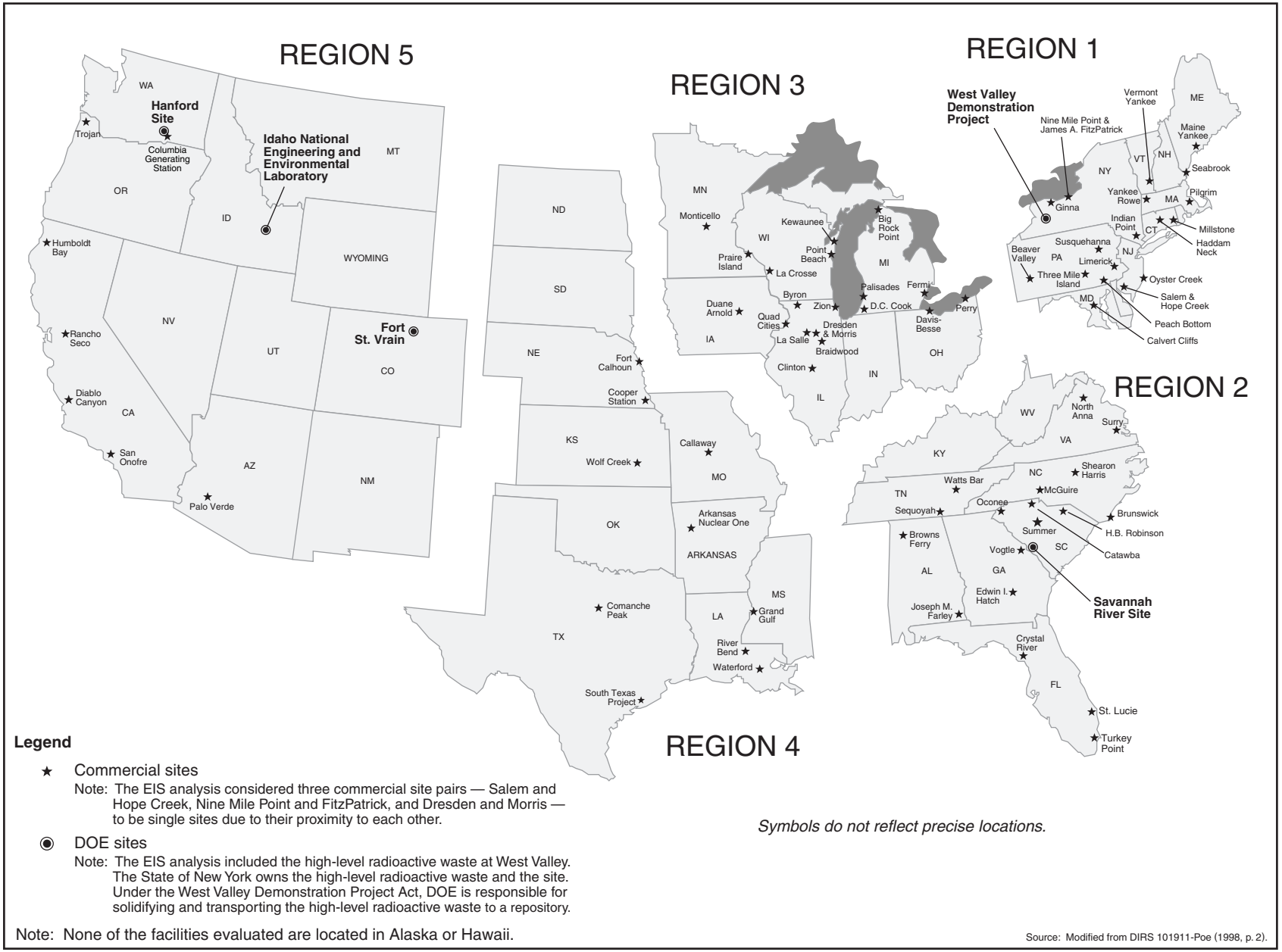

Figure K-2. No-Action Alternative analysis regions.

The primary cause of failure of surface-mounted concrete structures is freeze/thaw cycles that cause the concrete to crack and spall (break off in layers), which allows precipitation to enter the concrete, causing more freeze damage. *Freeze/thaw failure* is defined as the time when half of the thickness of the concrete is cracked and spalled. Some regions (coastal California, Texas, Florida, etc.) are essentially without the freeze/thaw cycle. In these locations the primary failure mechanism is precipitation containing chlorides, which decompose the chemical constituents of the concrete into sand-like materials. This process progresses more slowly than the freeze/thaw process. Figure K-3 shows estimated concrete storage module failure times.

Below-grade concrete structures, such as those used to store some of the DOE spent nuclear fuel and most of the high-level radioactive waste, would be affected by the same concrete degradation mechanisms as surface facilities. Below grade, the freeze/thaw degradation would not be as great because the soil would moderate temperature fluctuations. The primary failure mechanism for below-grade facilities would be the loss of the above-grade roof, which would result in precipitation seeping around shield plugs. The analysis assumed that this would occur 50 years after the end of facility maintenance, and that this would be the reasonable life expectancy of a facility without maintenance and periodic repair (DIRS 101910-Poe 1998, pp. 4-6 to 4-19).

K.2.1.2 Storage Canister Degradation

The second process analyzed was spent nuclear fuel and high-level radioactive waste storage canister degradation. For commercial and DOE spent nuclear fuel, the analysis defined failure of the stainless-steel dry storage canister as the time at which precipitation penetrated the canister and wet the spent nuclear fuel. The analysis defined failure for the high-level radioactive waste as the time at which precipitation penetrated the canisters. This is consistent with the repository definition that failure of the waste package would occur when water penetrated the package and came in contact with the contents. The stainless-steel model used for the No-Action analysis was consistent with the waste package inner layer corrosion model used for the repository TSPA-VA (DIRS 101779-DOE 1998, Volume 3, Section 3.4) with the functional parameters modified to incorporate stainless-steel corrosion data (Section K.4.3.1 discusses the sensitivity of outcome to carbon-steel dry storage containers). In addition, the analysis used parameters appropriate for above-ground conditions, including temperature, meteorological data, and chemical constituents in the atmosphere and precipitation. Although inconsistent with the assumptions used for the TSPA-VA, the analysis took credit for the protectiveness of the high-level radioactive waste canister because (1) it is the only container between the waste material and the environment and, (2) to ignore the protectiveness of this barrier would have resulted in a considerable overestimation of impacts. This approach is consistent with the decision, in the case of the No-Action Scenario 2 analysis, to provide a realistic radionuclide release rate where possible and to preclude the overestimation of the associated radiological human health impacts.

The primary determinants of stainless-steel corrosion for the different regions are the amount, the acidity, and the chloride concentration of the precipitation. The storage canisters degrade faster in the below-grade storage configuration than on the surface due to the higher humidity in the below-grade environment. The high-level radioactive waste canisters degrade faster than the spent nuclear fuel canisters because they are not as thick. The analysis evaluated three corrosion mechanisms—general corrosion, pitting corrosion, and crevice corrosion (DIRS 104597-Battelle 1998, Appendix A). Of the three, crevice corrosion would be the dominant failure mechanism for the regions analyzed. Corrosion rates and penetration times vary among the different regions of the country. The analysis calculated regional penetration times from the time at which it assumed that precipitation first would come in contact with the stainless steel. Table K-1 lists the results.

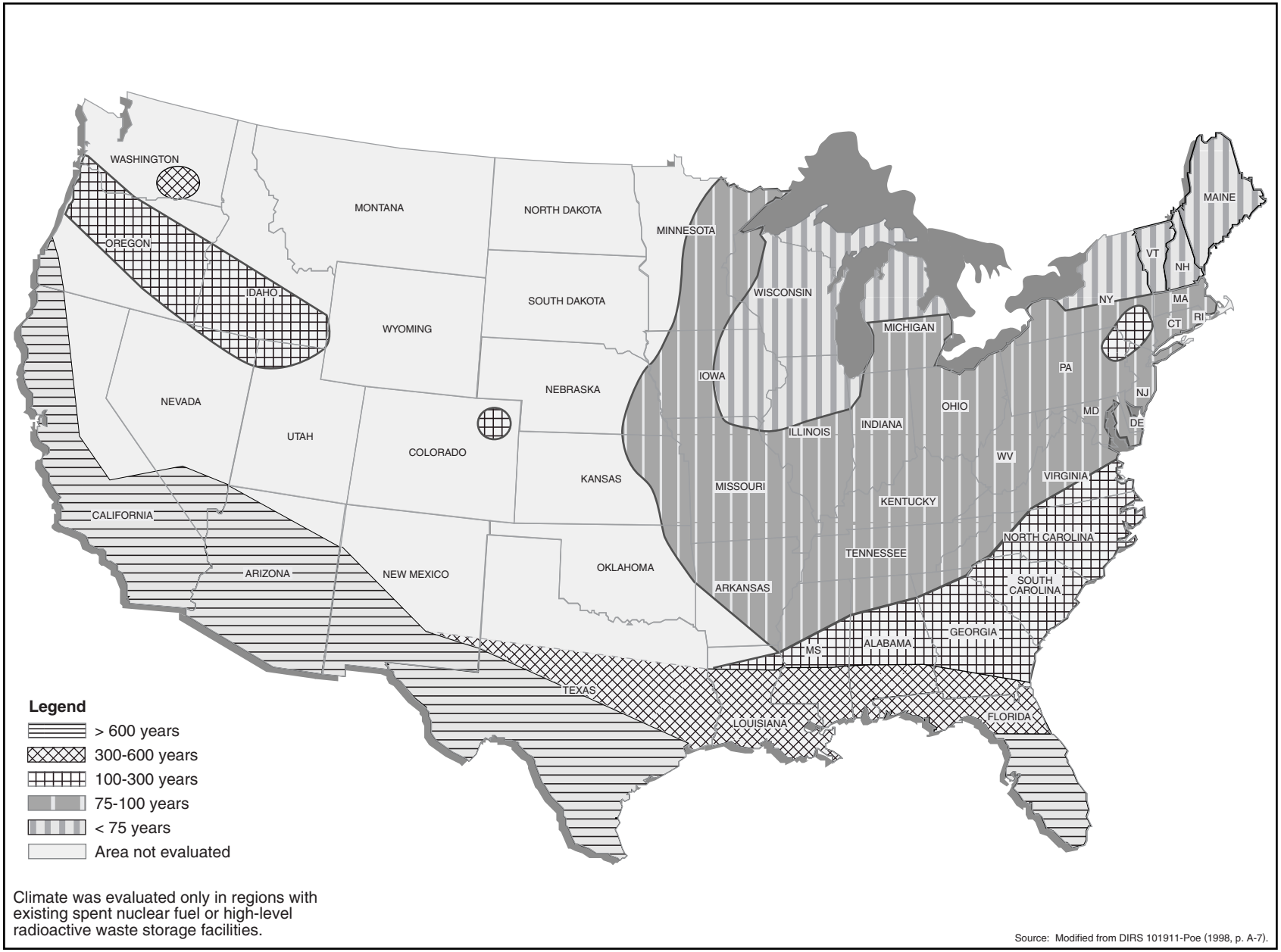

Figure K-3. Failure times for above-ground concrete storage modules.

Table K-1. Time (years) after the assumed loss of effective institutional control at which first failures would occur and radioactive materials could reach the accessible environment.

Material	Region	Storage facility	Weather[a] protection lost	Canister[b] breached (initial material release)
Commercial spent nuclear fuel	1	Surface	100	1,400
	2	Surface	700	1,500
	3	Surface	170	1,100
	4	Surface	750	1,600
	5	Surface	3,500	5,400
DOE spent nuclear fuel	2	Surface	700	1,400
	5	Surface	50	1,400
	5	Below grade	50	800
High-level radioactive waste	1	Surface	100	1,200
	2	Below grade	50	500
	5	Below grade	50	700

a. Source: Adapted from DIRS 101911-Poe (1998, Appendix A).
b. Source: DIRS 104597-Battelle (1998, data files, all); spent nuclear fuel dry storage or high-level radioactive waste canister.

K.2.1.3 Infiltration

The third process analyzes infiltration of water to the spent nuclear fuel and high-level radioactive waste. The amount of water in contact with these materials would be directly related to the size of the dry storage canister footprint and the mean (average) annual precipitation at each storage site. The rate of precipitation varies throughout the United States from extremely low (less than 25 centimeters [10 inches] per year) in the arid portions of the west to high (more than 150 centimeters [60 inches] per year) along the Gulf Coast in the southeast (Table K-2, Figure K-4). Local precipitation rates were used to determine the amount of water available that could cause dry storage canister and cladding failure, and spent nuclear fuel and high-level radioactive waste material dissolution.

Table K-2. Average regional precipitation.[a]

Region	Annual precipitation (centimeters)[b]	Percent of days with precipitation
1	110	30
2	130	29
3	80	33
4	110	31
5	30	24

a. Source: Adapted from DIRS 101911-Poe (1998, Appendix A, pp. A-13 to A-16).
b. To convert centimeters to inches, multiply by 0.3937.

K.2.1.4 Cladding

The fourth process analyzed was failure of the cladding, which is a protective barrier, usually metal (aluminum, zirconium alloy, stainless steel, nickel-chromium, Hastalloy, tantalum, or graphite), surrounding the spent nuclear fuel material to contain radioactive materials. For spent nuclear fuel, cladding is the last engineered barrier to be breached before the radioactive material can begin to be released to the environment.

K.2.1.4.1 *Commercial Spent Nuclear Fuel Cladding*

The principal cladding material used on commercial spent nuclear fuel is zirconium alloy. About 1.2 percent (of MTHM) of commercial spent nuclear fuel is stainless-steel clad (Appendix A,

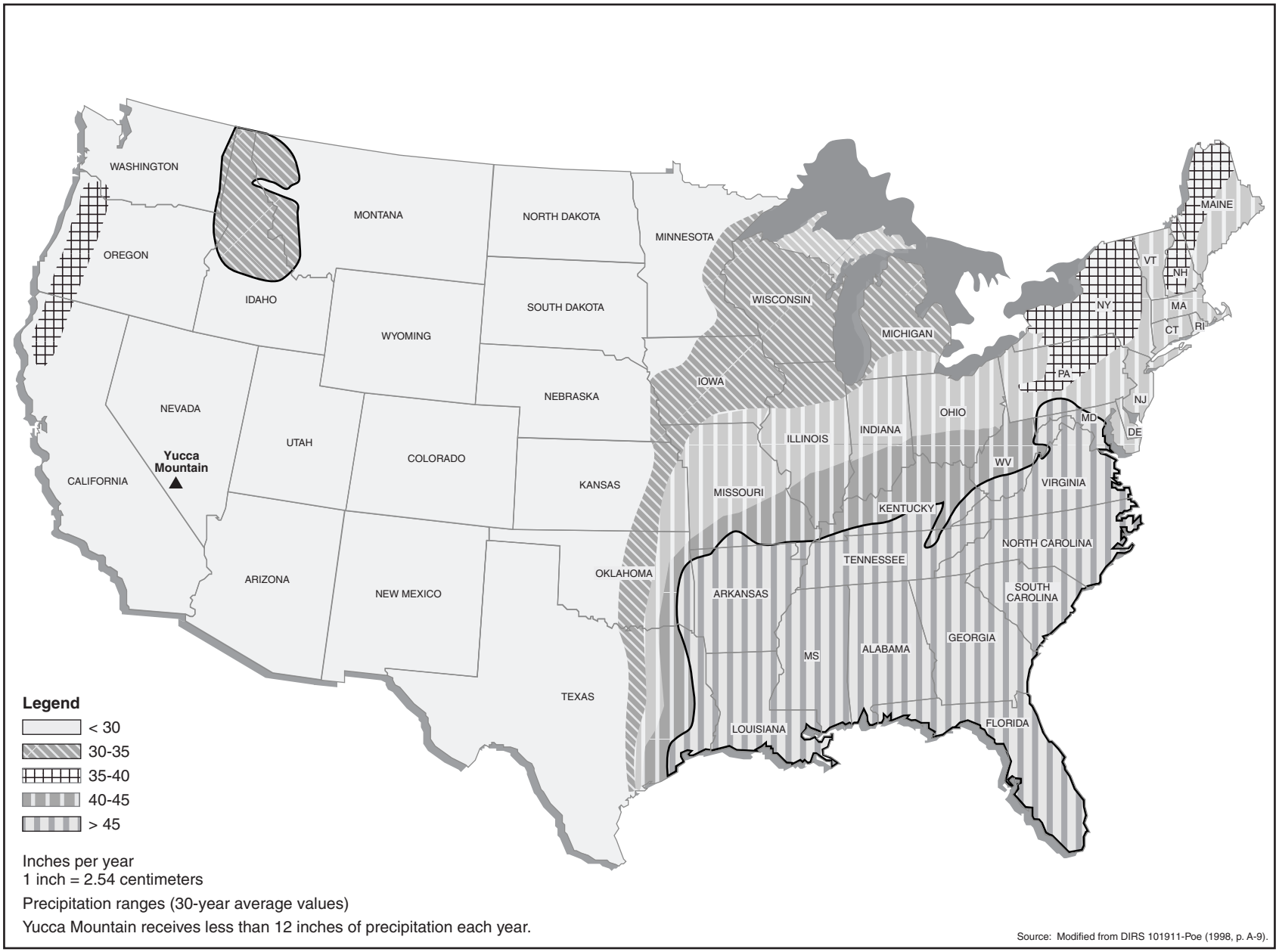

Figure K-4. Precipitation ranges for regions with existing spent nuclear fuel and high-level radioactive waste storage facilities.

Section A.2.1.5.3). To be consistent with the TSPA-VA, this analysis evaluated two cladding failure mechanisms: (1) so-called *juvenile failures* (failures existing at the start of the analysis period), and (2) *new failures* (failures that occur during the analysis period due to conditions in the storage container). The analysis assumed that juvenile failures existed in 0.1 percent of the zirconium alloy-clad spent nuclear fuel and in all of the stainless-steel-clad fuel at the beginning of the analysis period, and that after failure the cladding would offer no further protection to the radioactive material [this is consistent with the Viability Assessment assumption (DIRS 101779-DOE 1998, Volume 3, p. 3-97)].

Figure K-5 shows new failures (expressed as percent of commercial spent nuclear fuel over time) of zirconium alloy cladding, which were modeled using the median value assumed in the TSPA-VA cladding abstraction (DIRS 100362-CRWMS M&O 1998, pp. 6-19 to 6-54) for zirconium alloy corrosion. The Viability Assessment (DIRS 101779-DOE 1998, Volume 3, all) defines this information as a "fractional multiplier," which is calculated from the fraction of the failed fuel pin surface area. In the No-Action analysis, this corrosion is assumed to commence when weather protection afforded by the waste package is lost and the cladding is exposed to environmental precipitation. The TSPA-VA also considers cladding failure from creep strain, delayed hydride cracking, and mechanical failure from rock falls. These additional mechanisms normally occur after the 10,000-year analysis period and are therefore not considered in the No-Action analysis. As shown in Figure K-5, during the 10,000-year analysis period, less than 0.01 percent of the zirconium alloy-clad spent nuclear fuel would be expected to fail. If the upper limit curve from Figure 4 of the TSPA-VA cladding abstraction (DIRS 100362-CRWMS M&O 1998, pp. 6-19 to 6-54) was used, the value could be as high as 0.5 percent of the zirconium alloy-clad spent nuclear fuel. The lower limit value from the TSPA-VA cladding abstraction curve would be much less than 0.001 percent.

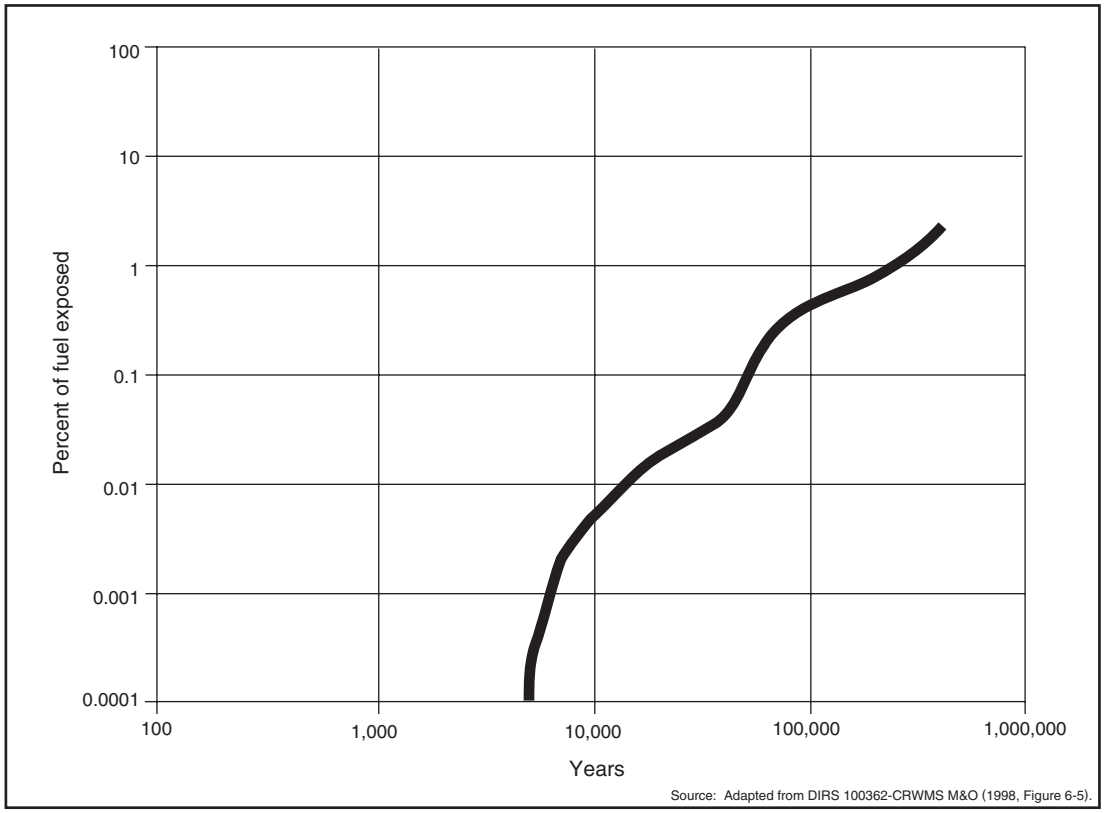

Figure K-5. Percent of commercial spent nuclear fuel exposed over time due to new failures.

K.2.1.4.2 *DOE Spent Nuclear Fuel Cladding*

The composition and cladding materials of DOE spent nuclear fuel vary widely. The cladding assumption for the surrogate material used in this analysis is identical (no cladding credit) to the assumption used in the TSPA-VA analysis (see Section K.4.3.1 for the discussion of uncertainty in relation to cladding).

K.2.1.5 Dissolution of Spent Nuclear Fuel and High-Level Radioactive Waste

The fifth process analyzed was the dissolution of the spent nuclear fuel and high-level radioactive waste. The rate of release of radionuclides from these materials would be related directly to the amount of surface area exposed to moisture, the quantity and chemistry of available water, and temperature. The TSPA-VA process model, modified to reflect surface environmental conditions (temperature, relative humidity, etc.), was used to estimate release rates from the exposed spent nuclear fuel and high-level radioactive waste. The model and application to surface conditions is described in detail in Battelle (DIRS 104597-Battelle 1998, pp. 2.9 to 2.11).

K.2.1.5.1 *Commercial Spent Nuclear Fuel Dissolution*

Consistent with the repository impact analysis, this analysis estimated that new zirconium alloy failures would begin late in the 10,000-year period (see Figure K-5). As discussed in Section K.2.1.4.1, only 0.01 percent of the zirconium alloy-clad spent nuclear fuel would be likely to fail during the 10,000-year analysis period. Therefore, most of the exposed material considered in this analysis would result from juvenile failures of zirconium alloy- and stainless-steel-clad spent nuclear fuel.

K.2.1.5.2 *DOE Spent Nuclear Fuel Dissolution*

The analysis assumed that DOE spent nuclear fuel would be a metallic uranium fuel with zirconium alloy cladding (a representative or surrogate fuel that consisted primarily of N-Reactor fuel). Consistent with the repository input analysis, the No-Action Scenario 2 analysis takes no credit for the cladding. The analysis used the TSPA-VA model for metallic uranium fuel, modified for surface environmental conditions, to predict releases of the DOE spent nuclear fuel.

K.2.1.5.3 *High-Level Radioactive Waste Dissolution*

Most high-level radioactive waste would be stored in below-grade concrete vaults. As discussed in Section K.2.1.1, these vaults would be exposed to precipitation as soon as weather protection was lost (the model assumed this would occur 50 years after loss of institutional control). After the loss of weather protection and failure of the stainless-steel canisters, the high-level radioactive waste would be exposed to precipitation. The environment in the underground vault would be humid and deterioration would occur. Thus, the material would be exposed to either standing water or humid conditions in the degrading vaults after the canister failed. The borosilicate glass deterioration model used in this analysis was the same as the TSPA-VA model modified to reflect surface conditions (temperature and precipitation chemistry).

K.2.1.6 Regionalization of Sites for Analysis

The climate of the contiguous United States varies considerably across the country. The release rate of the radionuclide inventory would depend primarily on the interactions between environmental conditions (rainfall, freeze-thaw cycles) and engineered barriers. To simplify the analysis, DOE divided the country into five regions (see Figure K-2) (DIRS 101911-Poe 1998, p. 2).

The analysis assumed that a single hypothetical site in each region would store all the spent nuclear fuel and high-level radioactive waste existing in that region. Such a site does not exist but is a mathematical construct for analytical purposes. To ensure that the calculated results for the regional analyses reflect appropriate inventory, facility and material degradation, and radionuclide transport, the spent nuclear fuel and high-level radioactive waste inventories, engineered barriers, and environmental conditions for the hypothetical sites were developed from data for each of the existing sites in the given region. Weighting criteria to account for the amount and types of spent nuclear fuel and high-level radioactive waste at each site were used in the development of the environmental data for the regional site, such that the results of the analyses for the hypothetical site were representative of the sum of the results of each actual site if they had been modeled independently (DIRS 101911-Poe 1998, p. 1). If there are no storage facilities in a particular area of the country, the environmental parameters of that area were not evaluated.

Table K-3 lists the Proposed Action and Module 1 quantities of commercial spent nuclear fuel, DOE spent nuclear fuel, and high-level radioactive waste in each of the five regions. The values in Table K-1 are the calculated results of failures of the various components of the protective engineered barriers and release of radioactive material in each region.

Table K-3. Proposed Action and Module 1 quantities of spent nuclear fuel (metric tons of heavy metal) and canisters of high-level radioactive waste in each geographic region.[a,b]

	Commercial spent nuclear fuel[c]								
	Region total[d]		With juvenile cladding failure		Stainless-steel cladding	DOE spent nuclear fuel[e]		High-level radioactive waste[f]	
Region	Proposed Action (MTHM)	Module 1 (MTHM)	Proposed Action (MTHM)	Module 1 (MTHM)	Proposed Action and Module 1 (MTHM)	Proposed Action (MTHM)	Module 1 (MTHM)	Proposed Action[g] (canisters)	Module 1[g] (canisters)
1	16,800	27,000	16	27	410			300	300
2	18,900	31,800	19	32	0	30	45	6,000	6,200
3	15,000	22,900	15	23	170				
4	7,200	14,100	7	14	0				
5	5,400	9,600	5	9	140	2,300	2,455	2,000	15,500
Totals	***63,000***	***105,000***	***62***	***105***	***720***	***2,300***	***2,500***	***8,300***	***22,000***

a. Source: Appendix A.
b. Totals might differ from sums due to rounding.
c. All analyzed as stored on surface as shown on Chapter 2, Figures 2-32, 2-33, and 2-34.
d. Includes plutonium in mixed-oxide spent nuclear fuel, which is assumed to behave like other commercial spent nuclear fuel.
e. A representative or surrogate fuel that consisted primarily of N-reactor fuel.
f. Includes immobilized plutonium.
g. Historically, a canister of high-level radioactive waste has been assumed to be equivalent to about 0.5 MTHM (see Appendix A, Section A.2.3.1).

K.2.2 RADIONUCLIDE RELEASE

The sixth and final step in the process is the release of radioactive materials to the environment. The anticipated release rates (fluxes) were estimated in terms of grams per 70-year period (typical human life expectancy in the United States) of uranium dioxide, uranium metal, or borosilicate glass for commercial spent nuclear fuel, DOE spent nuclear fuel, and high-level radioactive waste, respectively. To assess potential lifetime impacts on human receptors, the amount of fission products and transuranics associated with gram quantities of uranium dioxide, uranium metal, and borosilicate glass were calculated for approximately 140 consecutive 70-year average human lifetimes to determine releases from the 10,000-year analysis period. Weighting criteria were used to ensure appropriate contributions by the different types of spent nuclear fuel and the high-level radioactive waste in each region, as appropriate.

The result was a single release rate for each region that accounted for the different materials (uranium dioxide, uranium metal, and borosilicate glass).

The radionuclide distributions in the spent nuclear fuel and high-level radioactive waste (Appendix A) were used for these analyses. These were expressed as radionuclide-specific curies for storage packages (assembly or canister). The curies per storage package were converted to curies per gram of uranium dioxide, uranium metal, or borosilicate glass (as described above for each spent nuclear fuel and high-level radioactive waste material). This radionuclide distribution was multiplied by release flux (curies of spent nuclear fuel and high-level radioactive waste material per 70-year period) after being corrected for decay and the ingrowth of decay products for various times after disposal. These corrections were determined using the ORIGEN computer program (DIRS 147923-RSIC 1991, all) for each of the approximately 140 consecutive 70-year human lifetimes to determine the release over the 10,000-year period. The results of the ORIGEN runs were used as input to the environmental transport program.

DEFINITIONS

Fission products: Radioactive or non-radioactive atoms that are produced by the fission (splitting) of heavy atoms, such as uranium.

Transuranics: Radioactive elements, heavier than uranium, that are produced in a nuclear reactor when uranium atoms absorb neutrons rather than splitting. Examples of transuranics include plutonium, americium, and neptunium.

Curie: The basic unit of radioactivity. It is equal to the quantity of any radionuclide in which 37 billion atoms are decaying per second.

Specific activity: An expression of the number of curies of activity per gram of a given radionuclide. It is dependent on the half life and molecular weight of the nuclide.

In addition to the isotopes identified in the repository inventory specified in Appendix A, the No-Action Scenario 2 analysis considered 167 other isotopes in the light-water reactor radiological database (DIRS 102588-DOE 1992, p. 1.1-1). Of the 220 isotopes evaluated, six would contribute more than 99.5 percent of the total dose. Table K-4 lists these six isotopes along with technetium-99, which individually would contribute less than 0.003 percent of the total dose. Plutonium-239 and -240 would contribute more than 96 percent of the radiological impacts during the 10,000-year analysis period because of their very large dose conversion factors. Americium-241 and -243 would be minor contributors to the dose. Neptunium-237 and technetium-99 were of tertiary importance (Table K-4).

Table K-4. Radionuclides and relative contributions over 10,000 years to Scenario 2 impacts.[a]

Isotope	Percent of total dose
Americium-241	3.2
Americium-243	0.86
Neptunium-237	0.29
Plutonium-238	0.2
Plutonium-239	49.0
Plutonium-240	47.0
Technetium-99	< 0.003

a. Source: DIRS 101935-Toblin (1999, p. 6).

K.2.3 ENVIRONMENTAL TRANSPORT OF RADIOACTIVE MATERIALS

Radioactive materials in degraded spent nuclear fuel and high-level radioactive waste could be transported to the environment surrounding each storage facility by three pathways: groundwater, surface-water runoff, and atmosphere. Figure K-6 shows the potential exposure pathways. The analysisassumed that existing local climates would persist throughout the time of exposure of the spent nuclear fuel and high-level radioactive waste to the environment. The assumed configuration for the

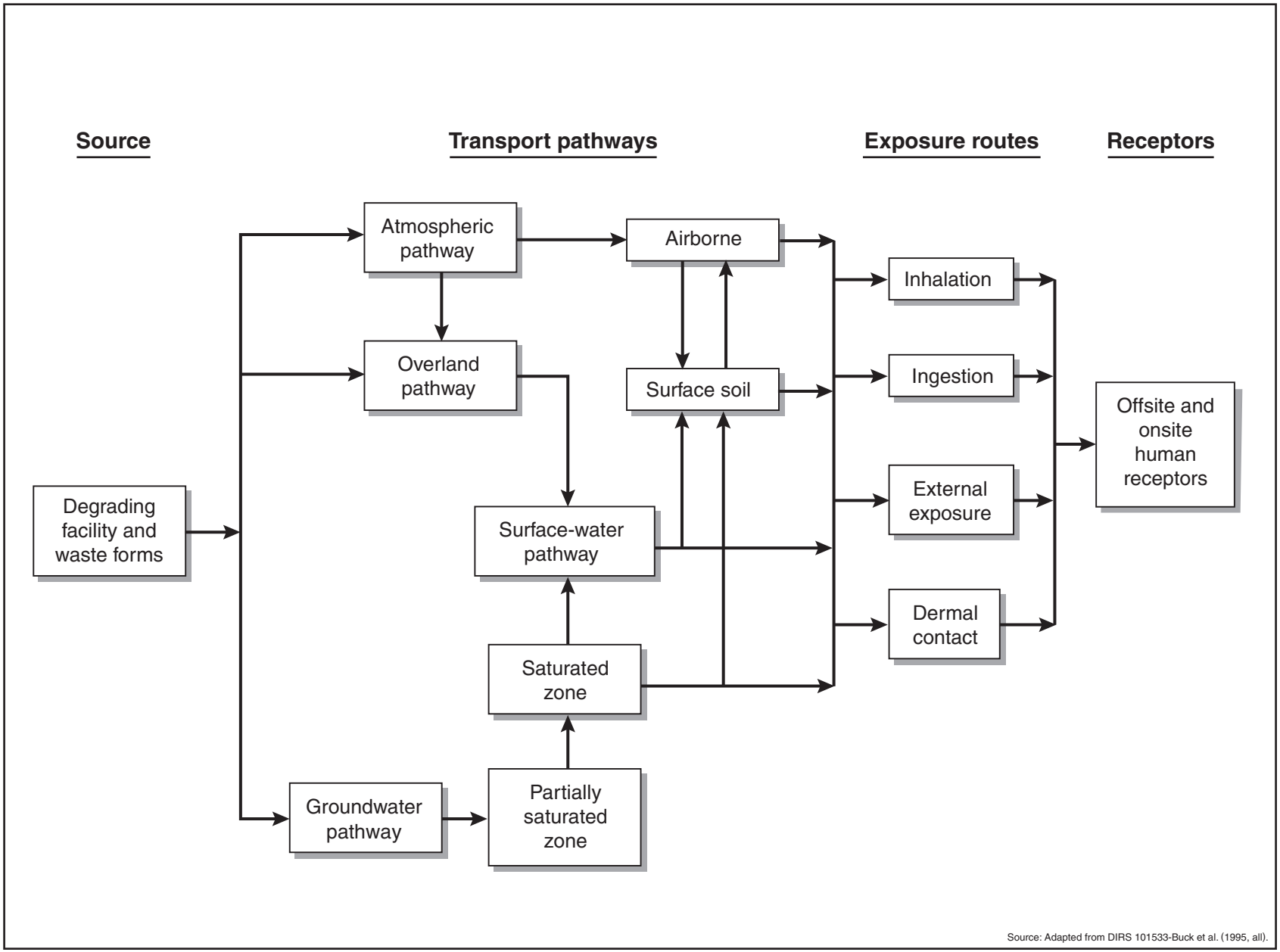

Figure K-6. Potential exposure pathways associated with degradation of spent nuclear fuel and high-level radioactive waste.

degraded storage facilities would have debris covering the radioactive material, which would remain inside the dry storage canisters. While the dry storage canisters could fail sufficiently to permit water to enter, they probably would retain their structural characteristics, thereby minimizing the dispersion of radioactive particulate material to the atmosphere (DIRS 147905-Mishima 1998, p. 4). Based on this analysis, the airborne particulate pathway generally would not be an important source of human exposure. The assumption is that after radionuclides dissolved in the precipitation they would reach the environment either through groundwater or surface-water transport.

The analysis performed environmental fate and transport pathway modeling using the Multimedia Environmental Pollutant Assessment System program (DIRS 101533-Buck et al. 1995, all). The Multimedia Environmental Pollutant Assessment System is an integrated system of analytical, semianalytical, and empirically based mathematical models that simulate the transport and fate of radioactive materials through various environmental media and calculate concentrations, doses, and health effects at designated receptor locations.

The Multimedia Environmental Pollutant Assessment System was originally developed by Pacific Northwest National Laboratory to enable DOE to prioritize the investigation and remediation of the Department's hazardous, radioactive, and mixed waste sites in a scientific and objective manner based on readily available site information. The Multimedia Environmental Pollutant Assessment System has evolved into a widely accepted (by Federal and international agencies) computational tool for calculating the magnitude of environmental concentrations and public health impacts caused by releases of radioactive material from various sources.

The following sections discuss the assumptions and methods used to determine radioactive material transport for groundwater and surface-water pathways. Environmental parameters defined for input to the Multimedia Environmental Pollutant Assessment System program were collected from various sources for specific sites (DIRS 101925-Sinkowski 1998, p. 2) and regionalized parameters were developed (DIRS 101912-Poe and Wise 1998, all). The analysis used long-term averages to represent environmental conditions, and assumed that these parameters would remain constant over the 10,000-year analysis period. The following sections discuss the method for each pathway.

K.2.3.1 Groundwater Transport

Precipitation falling on degrading spent nuclear fuel and high-level radioactive waste material would form a radioactive solution (leachate) that could migrate through the vadose zone (the unsaturated upper layer of soil) to the underlying water table, which would dilute, disperse, and transport the material downgradient through the local aquifer system. As a result, there is a potential for human exposure through the groundwater pathway to downgradient well users and to populations along surface-water bodies where groundwater feeds into surface water.

The groundwater component of the radioactive material fluxes (infiltration) averaged over 70-year (lifetime) increments was entered in the Multimedia Environmental Pollutant Assessment System program. The infiltration would carry the contaminated leachate down through the vadose zone to the saturated zone (aquifer). The contaminants would be diluted and dispersed as they traveled through the aquifer. Radioactive material retardation would occur in both the unsaturated (above the water table) and saturated (below the water table) zones. A distribution adsorption (that is, surface retention) coefficient, K_d, (the amount of material adsorbed to soil particles relative to that in the water) modeled this retardation (DIRS 101935-Toblin 1999, p. 2). This coefficient is radioactive material-specific and varies for each material based on such factors as soil pH and clay content.

Table K-5 lists the adsorption coefficients, K_d, for the elements explicitly modeled for groundwater transport. The coefficients are expressed as a function of the clay content of the soil through which the

Table K-5. Multimedia Environmental Pollutant Assessment System default elemental equilibrium adsorption coefficients (K_d; milliliters per gram) for soil pH between 5 and 9.[a]

Element	Clay content by weight		
	< 10 percent	10 to 30 percent	≥ 30 percent
Actinium	228	538	4,600
Americium	82	200	1,000
Californium	0	0	0
Carbon	0	0	0
Cesium	51	249	270
Chlorine	0	0	0
Cobalt	2	9	200
Curium	82	200	1,000
Iodine	0	0	0
Krypton	0	0	0
Lead	234	597	1,830
Neptunium	3	3	3
Nickel	12	59	650
Niobium	50	100	100
Palladium	0	4	40
Plutonium	10	100	250
Protactinium	0	50	500
Radium	24	100	124
Ruthenium	274	351	690
Samarium	228	538	4,600
Selenium	6	15	15
Strontium	24	100	124
Technetium	3	20	20
Thorium	100	500	2,700
Tin	5	10	10
Tritium	0	0	0
Uranium	0	50	500
Zirconium	50	500	1,000

a. Source: DIRS 101935-Toblin (1999, p. 2).

elements are being transported; the analyses assumed a soil pH between 5 and 9. Note that the K_d values of all isotopes of a given element (for example, plutonium-238, -239, and -240) are the same, because adsorption is a chemical rather than nuclear process.

The time required to traverse the groundwater was determined for each radionuclide. Tables K-6 and K-7 list the range of nuclide groundwater transport times, from source to receptor, for each of the five regions. Times are listed for the important nuclides (see Table K-4). The analysis assumed that the vadose/aquifer flow fields were steady-state, so that the nuclide travel times at a particular site would be constant over the 10,000-year analysis period, although the nuclide release rates were not. Table K-6 lists parameters describing the total (over the analysis period) and maximum nuclide release rates for the same important nuclides. Region 5, dominated by two large DOE sites, is seen to result in the largest nuclide releases of all of the regions.

Table K-7 also lists the number of water systems and people that would obtain water from the affected waterways. Many of these people would be subject to impacts from more than one site because they would obtain their water from affected waterways downstream from multiple sites.

When the groundwater reached the point where it outcropped to surface water, radioactive material transport would be subject to further dilution and dispersion. For most of the regions analyzed, the

Table K-6. Regional source terms and environmental transport data for important isotopes used for collective drinking water radiological impact analysis.[a]

Parameter	Plutonium-239/240	Plutonium-238	Americium-241	Americium-243	Neptunium-237	Technetium-99
Nuclide released in 10,000 years (curies)						
Region 1	4,200	20	660	115	8.9	98
Region 2	17,000	97	1,500	240	32	1,200
Region 3	130,000	660	31,000	3,300	260	2,600
Region 4	4,300	17	450	110	9.0	89
Region 5	570,000	180	42,000	1,700	720	6,500
Maximum annual nuclide release (curies per year)						
Region 1	19	0.020	1.2	0.053	0.0031	0.034
Region 2	53	0.035	2.2	0.11	0.0083	0.19
Region 3	60	0.71	56	1.6	0.092	1.0
Region 4	0.20	0.016	0.78	0.054	0.0034	0.035
Region 5	140	0.22	66	0.47	0.14	1.4
Years (from 2016) of maximum annual nuclide release						
Region 1	1,435	1,435	1,435	1,435	1,435	1,435
Region 2	1,575	1,575	1,575	1,575	1,575	1,575
Region 3	1,155	1,155	1,155	1,155	1,155	1,155
Region 4	1,715	1,715	1,715	1,715	1,715	1,715
Region 5	875	875	875	875	875	875
Nuclide reaching receptors in 10,000 year (curies)						
Region 1	3,600	11	130	43	8.8	95
Region 2	13,000	10	1.4	39	31	1,100
Region 3	110,000	250	380	510	250	2,500
Region 4	2,000	3.6	0.66	24	6.0	59
Region 5	180,000	2.6	0.020	1.2	630	5,600
Nuclide transport time[b] (years)						
Region 1	10-5,500	10-5,500	10-45,000	10-45,000	10-1,700	10-1,700
Region 2	460-9,000	460-9,000	2,000-36,000	2,000-36,000	43-860	140-1,500
Region 3	65-45,000	65-45,000	410-260,000	410-260,000	31-9,800	31-9,800
Region 4	850-520,000	850-520,000	3,000-1,000,000	3,000-1,000,000	59-16,000	130-100,000
Region 5	1,400-26,000	1,400-26,000	2,700-220,000	2,700-220,000	44-8,000	280-8,000

a. Source: DIRS 101935-Toblin (1999, p. 4).
b. Time from source to receptor.

Table K-7. Transport and population data for drinking water pathway impact analysis.

Parameter	Region 1	Region 2	Region 3	Region 4	Region 5
Groundwater flow time (years)[a]	2.0 - 59	4.6 - 37	1.8 - 420	4.6 - 960	2.9 - 190
Number of people that would obtain domestic water supply from affected waterways (millions)[b]	6.7	5.3	13.1	5.3	0.16
Affected drinking water systems[c]	112	147	137	64	23

a. From source to outcrop; Source: Adapted from DIRS 101852-Jenkins (1998, Table 2).
b. Source: DIRS 101911-Poe (1998, p. 12).
c. Source: Adapted from DIRS 101925-Sinkowski (1998, all).

distance between the storage location and the downgradient surface-water body would be inside the site boundary; therefore, offsite wells generally would not be affected. However, the analysis calculated groundwater concentrations for hypothetical onsite and offsite receptors. The Multimedia Environmental Pollutant Assessment System program calculated groundwater and surface-water concentrations at each receptor location for consecutive 70-year lifetimes in the 10,000-year analysis period.

The parameters necessary for the spent nuclear fuel and high-level radioactive waste storage sites for the Multimedia Environmental Pollutant Assessment System were defined. Pertinent hydrologic and hydrogeologic information was derived from the site-specific Updated Final Safety Analysis Reports for commercial nuclear sites and site-specific data provided by the various DOE sites (DIRS 101852-Jenkins 1998, p. 1).

Table K-8 lists the range (over the individual sites) in each region of the important hydrogeologic parameters that would affect the transport of the radionuclides through the groundwater. These parameters form the basis for the nuclide transport times listed in Table K-7.

Table K-8. Multimedia Environmental Pollutant Assessment System regional groundwater input parameters.[a]

Parameter	Region 1	Region 2	Region 3	Region 4	Region 5
Vadose zone					
Contaminated liquid infiltration rate (vertical Darcy velocity) (feet per year)[b]	3.1 - 3.5	4.4	2.7 - 3.1	2.7 - 4.4	0.88 - 3.1
Clay content (percent)	0 - 15	1 - 47	1 - 47	3 - 15	0 - 15
pH of pore water	5 - 9	5 - 9	5 - 9	5 - 9	5 - 9
Thickness (feet)	6 - 40	5 - 70	4 - 31	5 - 50	23 - 250
Bulk density (grams per cubic centimeter)	1.4 - 1.9	1.4 - 1.6	1.4 - 1.6	1.4 - 1.6	1.4 - 1.7
Total porosity (percent)	5 - 46	38 - 49	38 - 49	38 - 46	38 - 49
Field capacity (percent)	2.5 - 28	9 - 42	9 - 42	9 - 28	3 - 28
Saturated hydraulic conductivity (feet per year)	210 - 6,800	27 - 6,800	27 - 6,800	210 - 6,800	72 - 6,800
Aquifer					
Clay content (percent)	0 - 10	0 - 47	0 - 15	0 - 15	0 - 10
pH of pore water	5 - 9	5 - 9	5 - 9	5 - 9	5 - 9
Thickness (feet)	6 - 120	10 - 85	7 - 160	20 - 150	25 - 250
Bulk density (grams per cubic centimeter)	1.6 - 2.1	1.4 - 2.0	1.5 - 1.7	1.4 - 1.7	1.5 - 1.9
Total porosity (percent)	5 - 44	5 - 49	5 - 46	5 - 46	23 - 44
Effective porosity (percent)	2.9 - 22	2.9 - 28	2.9 - 25	22 - 27	13 - 25
Saturated hydraulic conductivity (feet per year)	210 - 6,800	27 - 6,800	27 - 6,800	210 - 6,800	72 - 6,800
Darcy velocity (feet per year)	6.8 - 1,400	12 - 170	3.9 - 430	0.58 - 270	33 - 560
Travel distance (feet)	1,900 - 5,600	2,000 - 4,700	1,900 - 23,000	1,600 - 12,000	1,900 - 37,000

a. Source: Adapted from DIRS 101852-Jenkins (1998, Table 2).
b. Annual precipitation rate (through degraded structure).

A simplifying analytical assumption was that radioactive material transport would occur only through the shallowest aquifer beneath the site. Because this assumption limits the interchange of groundwater with underlying aquifers, less radioactive material dilution would occur, and groundwater pathway impacts could be slightly overestimated. However, because impacts from the groundwater pathway would be minor in comparison to surface-water pathways, the total estimated impacts would not be affected by this assumption.

K.2.3.2 Surface-Water Transport

The amount of leachate from degraded spent nuclear fuel and high-level radioactive waste in the surface-water pathway would depend on soil characteristics and the local climate. The Multimedia Environmental Pollutant Assessment System considers precipitation rates (Table K-2), soil infiltration, evapotranspiration, and erosion management practices to determine the amount of leachate that would run off rather than percolate into the soil. The contaminated runoff would travel overland and eventually enter nearby rivers and streams that would dilute it further.

To determine the impacts of the contaminated discharge to surface water on the downstream populations using that water (affected populations), DOE calculated the surface water flow rate and the release rate of contaminants (as curies per year) contributed by each storage location draining to the surface water. Using these values, DOE determined surface-water radionuclide concentrations for each receptor location. DOE applied these concentrations to the respective affected populations to estimate impacts for each region.

K.2.3.3 Atmospheric Transport

If degraded spent nuclear fuel or high-level radioactive waste was exposed to the environment, small particles could become suspended in the air and transported by wind. The Multimedia Environmental Pollutant Assessment System methodology includes formulations for radioactive material (particulate) suspension by wind, vehicular traffic, and other physical disturbances of the ground surface. The impacts from the atmospheric pathways would be small in comparison to surface-water pathways because the cover provided by the degraded structures and the relatively large particle size and density of the materials (see Section K.2.3) would preclude suspension by wind. Therefore, impacts from the transport of radioactive particulate materials were not included in the analysis.

K.2.4 HUMAN EXPOSURE AND DOSE CALCULATIONS

This section describes methods used in the No-Action Scenario 2 analysis to estimate dose rates and potential impacts to individuals and population groups from exposures to radionuclide contaminants in groundwater and surface water and in the atmosphere. As discussed above, these contaminated environmental media would result from the degradation of storage facilities (Sections K.2.1.1), corroding dry storage canisters (Section K.2.1.2), cladding failure (Section K.2.1.4), spent nuclear fuel and high-level radioactive waste dissolution (Section K.2.1.5), leachate percolation and groundwater transport (Section K.2.3.1), surface-water runoff (Section K.2.3.2), and atmospheric suspension and transport (Section K.2.3.3).

For Scenario 1 and the first 100 years of Scenario 2, the presence of effective institutional control would ensure that radiological releases to the environment and radiation doses to workers and the public remained within Federal limits and DOE Order requirements and were maintained as low as reasonably achievable. As a result, impacts to members of the public would be very small. Potential radiological human health impacts that could occur would be due primarily to occupational radiation exposure of onsite workers. The analysts estimated these impacts based on actual operational data from commercial nuclear powerplant sites (DIRS 101898-NRC 1991, pp. 22 to 25) and projected these impacts for the 100- and 10,000-year analysis periods for Scenario 1.

For Scenario 2, impacts to onsite workers and the public during institutional control (approximately 100 years) would be the same as those for Scenario 1. However, because the assumption for Scenario 2 is that there would be no effective institutional control after approximately 100 years, engineered barriers would begin to degrade and eventually would not prevent radioactive materials from the spent nuclear fuel and high-level radioactive waste from entering the environment. During the period of no effective institutional control, there would be no workers at the site. Thus, impacts were calculated only for the public.

For Scenario 2, the potential highest exposures and dose rates over a 70-year lifetime period were evaluated for individuals and exposed populations. In addition, the total integrated dose to the exposed population for the 10,000-year analysis period was estimated. Human exposure parameters (exposure times, ingestion and inhalation rates, agricultural activities, food consumption rates, etc.) were developed based on recommendations from Federal agencies (DIRS 101819-EPA 1988, pp. 113 to 131; DIRS 101820-EPA 1991, Attachment B; DIRS 100067-NRC 1977, pp. 1.109-1 to 1.109-2; DIRS 147925-

Shipers and Harlan 1989, all; DIRS 147915-NRC 1991, Chapter 6) and are reflected as Multimedia Environmental Pollutant Assessment System default values (DIRS 101533-Buck et al. 1995, Section 1.0). Other parameters chosen for this analysis are summarized in supporting documentation (DIRS 101925-Sinkowski 1998, all; DIRS 101935-Toblin 1999, all; DIRS 101936-Toblin 1999, all; DIRS 101937-Toblin 1998, all). Table K-9 lists the exposure and usage parameters for all of the pathways considered in the analysis (see Section K.3.1).

The Scenario 2 analysis evaluated long-term radiation doses and impacts to populations exposed through the surface-water and groundwater pathways. This analysis estimated population impacts only for the drinking water pathway using regionalized effective populations and surface-water dilution factors discussed in Section K.2.3.2. Other pathways were evaluated to determine their potential contribution in relation to drinking water doses. These analyses are discussed in Section K.3.1.

K.2.4.1 Gardener Impacts

To reasonably bound human health impacts resulting from human intrusion, two types of gardener were evaluated—the onsite gardener (10 meters [33 feet]) from the degrading storage facility) and the near-site gardener (5 kilometers [3 miles] from the degrading facility). The analysis had both of these hypothetical gardeners residing on the flow path for groundwater. The gardeners would obtain all their drinking water from contaminated groundwater, grow their subsistence gardens in contaminated soils, and irrigate them with the contaminated groundwater. The contaminated garden soils, suspended by the wind, would contaminate the surfaces of the vegetables consumed by the gardeners. The hypothetical onsite gardener would be the maximally exposed individual.

HUMAN INTRUSION

Spent nuclear fuel and high-level radioactive waste in surface or below-grade storage facilities would be readily accessible in the absence of institutional control. For this reason, DOE anticipates that both planned and inadvertent intrusions could occur. An example of the former would be the scavenger who searches through the area seeking articles of value; an example of the latter would be the farmer who settles on the site and grows agricultural crops with no knowledge of the storage structure beneath the soil. Intrusions into contaminated areas also could occur through activities such as building excavations, road construction, and pipeline or utility replacement.

Under the conditions of Scenario 2, intruders could receive external exposures from stored spent nuclear fuel and high-level radioactive waste that would grossly exceed current regulatory limits and, in some cases, could be sufficiently high to cause prompt fatalities. In addition, long-term and repeated intrusions, such as those caused by residential construction or agricultural activities near storage sites, could result in long-term chronic exposures that could produce increased numbers of latent cancer fatalities. These intrusions could also result in the spread of contamination to remote locations, which could increase the total number of individuals potentially exposed.

Calculations were performed using transport models described by DIRS 101533-Buck et al. (1995, all) for gardeners in each of the five analysis regions using regionalized source terms and environmental parameters. Therefore, calculated impacts to the regional gardener (maximally exposed individual) would not represent the highest impacts possible from a single site in a given region, but rather would reflect an average impact for the region. Details of the analysis are provided in DIRS 101937-Toblin (1998, all). The regional hydrogeologic parameters listed in Table K-10, together with transient nuclide release rates (the maximum of which is indicated in the table), were used to determine the radiological impacts to the regional gardener as a result of groundwater transport. The regional parameters were based on a curie-weighting of the individual site parameters for plutonium and americium. The exposure

Table K-9. Multimedia Environmental Pollutant Assessment System human exposure input parameters for determination of all pathways radiological impacts sensitivity analysis (page 1 of 2).[a]

Water source[b]	Surface water
Domestic water supply treatment[c]	Yes
Fraction of plutonium removed by water treatment[d]	0.3
Drinking water rate (liters per day per person)[e]	2
Irrigation rate (liters per square meter per month)[f]	100
Leafy vegetable consumption rate (kilograms per day per person)[g]	0.021
Other vegetable consumption rate (kilograms per day per person)	0.13
Meat consumption rate (kilograms per day per person)	0.065
Milk consumption rate (kilograms per day per person)	0.075
Finfish consumption rate (kilograms per day per person)	0.0065
Shellfish consumption rate (kilograms per day per person)	0.0027
Shoreline contact (hours per day per person)	0.033
Americium ingestion dose conversion factor (rem per picocurie)[h]	3.6×10^{-6}
Americium finfish bioaccumulation factor	250
Americium shellfish bioaccumulation factor	1,000
Americium meat transfer factor (days per kilogram)	3.5×10^{-6}
Americium milk transfer factor (days per liter)	4.0×10^{-7}
Neptunium ingestion dose conversion factor (rem per picocurie)	4.4×10^{-6}
Neptunium finfish bioaccumulation factor	250
Neptunium shellfish bioaccumulation factor	400
Neptunium meat transfer factor (days per kilogram)	5.5×10^{-5}
Neptunium milk transfer factor (days per liter)	5.0×10^{-6}
Technetium ingestion dose conversion factor (rem per picocurie)	1.5×10^{-9}
Technetium finfish bioaccumulation factor	15
Technetium shellfish bioaccumulation factor	5
Technetium meat transfer factor (days per kilogram)	8.5×10^{-3}
Technetium milk transfer factor (days per liter)	1.2×10^{-2}
Plutonium ingestion dose conversion factor (rem per picocurie)[i]	3.5×10^{-6}
Plutonium finfish bioaccumulation factor	250
Plutonium shellfish bioaccumulation factor	100
Plutonium meat transfer factor (days per kilogram)	5.0×10^{-7}
Plutonium milk transfer factor (days per liter)	1×10^{-7}
Yield of leafy vegetables [kilograms (wet) per square meter]	2.0
Yield of vegetables [kilograms (wet) per square meter]	2.0
Yield of meat feed crops [kilograms (wet) per square meter]	0.7
Yield of milk animal feed crops [kilograms (wet) per square meter]	0.7
Meat animal intake rate for feed (liters per day)	68
Milk animal intake rate for feed (liters per day)	55
Meat animal intake rate for water (liters per day)	50
Milk animal intake rate for water (liters per day)	60
Agricultural areal soil density (kilograms per square meter)	240
Retention fraction of activity on plants	0.25
Translocation factor for leafy vegetables	1.0
Translocation factor for other vegetables	0.1
Translocation factor for meat animal	0.1
Translocation factor for milk animal	1.0
Fraction of meat feed contaminated	1.0
Fraction of milk feed contaminated	1.0
Fraction of meat water contaminated	1.0
Fraction of milk water contaminated	1.0
Meat animal soil intake rate (kilograms per day)	0.5

Table K-9. Multimedia Environmental Pollutant Assessment System human exposure input parameters for determination of all pathways radiological impacts sensitivity analysis (page 2 of 2).[a]

Water source[b]	Surface water
Milk animal soil intake rate (kilograms per day)	0.5
Leafy vegetable growing period (days)	60
Other vegetable growing period (days)	60
Beef animal feed growing period (days)	30
Milk animal feed growing period (days)	30
Water intake rate while showering (liters per hour)	0.06
Duration of shower exposure (hours per shower)	0.167
Shower frequency (per day)	1.0
Thickness of shoreline sediment (meters)	0.04
Density of shoreline sediments (grams per cubic meter)	1.5
Shore width factor for shoreline external exposure	0.2

a. Source: DIRS 101936-Toblin (1999, pp. 4 and 5).
b. Groundwater for gardener.
c. No for gardener.
d. Zero for gardener.
e. To convert liters to gallons, multiply by 0.26418.
f. To convert liters per square meter to gallons per square foot, multiply by 0.00025.
g. To covert kilograms to pounds, multiply by 2.2046.
h. Sediment ingestion = 0.1 grams per hour (0.000022 pound per hour) during contact.
i. For plutonium-239/240.

Table K-10. Multimedia Environmental Pollutant Assessment System groundwater transport input parameters for estimating radiological impacts to the onsite and near-site gardener.[a]

Parameter	Region 1	Region 2	Region 3	Region 4	Region 5
Vadose zone					
Contaminated liquid infiltration rate (vertical Darcy velocity) (feet per year)[b,c]	3.5	4.4	2.7	3.5	0.88
Clay content (percent)	1	10	12	11	2
pH of pore water	5 - 9	5 - 9	5 - 9	5 - 9	5-9
Thickness (feet)	11	44	7.1	43	180
Longitudinal dispersivity (feet)	0.11	0.44	0.071	0.43	1.8
Bulk density (grams per cubic meter)[d]	1.6	1.5	1.5	1.5	1.6
Total porosity (percent)	38	42	44	45	41
Field capacity (percent)	9.3	15	23	21	12
Saturated hydraulic conductivity (feet per year)	6,500	660	1,700	1,000	5,900
Aquifer					
Clay content (percent)	1.8	6.5	1.2	4.4	0.69
pH of pore water	5 - 9	5 - 9	5 - 9	5 - 9	5 - 9
Thickness (feet)	45	50	37	64	210
Bulk density (grams per cubic meter)	1.6	1.8	1.6	1.6	1.7
Total porosity (percent)	38	40	38	35	30
Effective porosity (percent)	22	23	22	20	17
Darcy velocity (feet per year)	340	62	69	51	300
Longitudinal dispersivity (feet)	f(x)[e]	f(x)	f(x)	f(x)	f(x)
Lateral dispersivity (feet)	f(x) ÷ 3	f(x) ÷ 3	f(x) ÷ 3	f(x) ÷ 3	f(x) ÷ 3
Vertical dispersivity (feet)	f(x) ÷ 400	f(x) ÷ 400	f(x) ÷ 400	f(x) ÷ 400	f(x) ÷ 400
Maximum annual plutonium-239 and -240 release (curies per year)	4.9	0.24	3.8	0.32	2.1
Years (from 2016) of maximum annual plutonium release	1,365	1,575	1,155	1,715	875

a. Source: DIRS 101937-Toblin (1998, p. 2-4).
b. Annual precipitation rate (through degraded structure).
c. To convert feet to meters, multiply by 0.3048.
d. To convert grams per cubic meter to pounds per cubic foot, multiply by 0.0000624.
e. $f(x) = 2.72 \times (\log_{10}0.3048 \times x)^{2.414}$, where x = downgradient distance.

parameters in Table K-9 describe the radionuclide exposure to the gardener where applicable (for example, exposure parameters related to the fish are not applicable to the gardener).

K.2.4.2 Direct Exposure

The analysis evaluated potential external radiation dose rates to the maximally exposed individual for a commercial independent spent fuel storage installation because this type of facility would provide the highest external exposures of all the facilities analyzed in this appendix. Maximum dose rates over the 10,000-year analysis period were evaluated for each region. The maximally exposed individual was assumed to be 10 meters (about 33 feet) from an array of concrete storage modules containing 1,000 MTHM of commercial spent nuclear fuel. The maximum dose rate varied between regions depending on how long the concrete shielding would remain intact (Table K-1).

The direct gamma radiation levels were calculated (DIRS 101556-Davis 1998, all). To ensure consistency between this analysis and the TSPA-VA, the same radionuclides were used for the design of the Yucca Mountain Repository surface facility shielding (DIRS 104603-CRWMS M&O 1995, Attachment 9.5). Radionuclide decay and radioactive decay product ingrowth over the 10,000-year analysis period were calculated using the ORIGEN computer program (DIRS 147923-RSIC 1991, all).

Neutron emissions were not included because worst-case impacts (death within a short period of exposure) would be the same with or without the neutron component.

K.2.5 ACCIDENT METHODOLOGY

Spent nuclear fuel and high-level radioactive waste stored in above-ground dry storage facilities would be protected initially by the robust surrounding structure (either metal or concrete) and by a steel storage container that contained the material. Normal storage facility operations would be primarily passive because the facilities would be designed for cooling via natural convection. DOE evaluated potential accident and criticality impacts for both Scenario 1 (institutional control for 10,000 years) and Scenario 2 (assumption of no effective institutional control after approximately 100 years with deterioration of the engineered barriers initially protecting the spent nuclear fuel or high-level radioactive waste).

For Scenario 1, human activities at each facility would include surveillance, inspection, maintenance, and equipment replacement when required. The facilities and the associated systems, which would be licensed by the Nuclear Regulatory Commission, would have certain required features. License requirements would include isolation of the stored material from the environment and its protection from severe accident conditions (10 CFR 50.34). The Nuclear Regulatory Commission requires an extensive safety analysis that considers the impacts of plausible accident-initiating events such as earthquakes, fires, high winds, and tornadoes. No plausible accident scenarios have been identified that result in the release of radioactive material from the storage facilities (DIRS 103449-PGE 1996, all; DIRS 103177-CP&L 1989, all). In addition, the license would specify that facility design requirements include features to provide protection from the impacts of severe natural events. These requirements and analyses must demonstrate that the facilities can withstand the most severe wind loading (tornado winds and tornado-generated missiles) and flooding from the Probable Maximum Hurricane with minimal release of radioactive material. This analysis assumed maintenance of these features indefinitely for the storage facilities.

DOE performed a scoping analysis to identify the kinds of events that could lead to releases of radioactive material to the environment prior to degradation of concrete storage modules and found none. The two events determined to be the most challenging to the integrity of the concrete storage modules would be the crash of an aircraft into the storage facility and a severe seismic event.